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Abstract. The HelioClim-3 database (HC3v3) provides records of surface solar irradiation every 15 min, estimated by processing images from the geostationary meteorological Meteosat satellites using climatological data sets of the atmospheric Linke turbidity factor. This technical note proposes a method to improve a posteriori HC3v3 by combining it with data records of the irradiation under clear skies from the new McClear clear-sky model, whose inputs are the advanced global aerosol property forecasts and physically consistent total column content in water vapour and ozone produced by the MACC (Monitoring Atmosphere Composition and Climate) projects. The method is validated by comparison with a series of ground measurements for 15 min and 1 h for 6 stations and for daily irradiation for 23 stations. The correlation coefficient is large, greater than respectively 0.92, 0.94, and 0.97, for 15 min, 1 h and daily irradiation. The bias ranges from −4 to 4 % of the mean observed irradiation for most sites. The relative root mean square difference (RMSD) varies between 14 and 38 % for 15 min, 12 and 33 % for 1 h irradiation, and 6 and 20 % for daily irradiation. As a rule of thumb, the farther from the nadir of the Meteosat satellite located at latitude 0° and longitude 0°, and the greater the occurrence of fragmented cloud cover, the greater the relative RMSD. The method improves HC3v3 in most cases, and with no degradation in the others. A systematic correction of HC3v3 with McClear is recommended.

1 Introduction

The downwelling solar irradiance observed at ground level on horizontal surfaces and integrated over the whole spectrum (total irradiance) is called surface solar irradiance (SSI). It is the sum of the direct irradiance from the direction of the sun and the diffuse from the rest of the sky vault, and is also called the global irradiance. The SSI is an essential climate variable (ECV) as established by the Global Climate Observing System in August 2010 (GCOS, 2013). Knowledge of the SSI and its geographical distribution is of prime importance for numerous domains where SSI plays a major role, as e.g. in weather, climate, biomass, and energy.

The HelioClim project is an ambitious initiative of MINES ParisTech launched in 1997 to increase knowledge about the SSI and to offer SSI values for any site, any instant over a large geographical area, and a long period of time, to a wide audience (Blanc et al., 2011). The project comprises several databases that cover Europe, Africa and the Atlantic Ocean. The HelioClim-1 (HC1) database offers daily means of the global SSI for the period 1985–2005. The HelioClim-3 (HC3) database contains 15 min values of the global SSI. It was created in 2004, and is updated daily from images taken by the Meteosat Second Generation satellites. Its recent improvements have taken place in the framework of the European MACC and MACC-II (Monitoring Atmosphere Composition and Climate) projects funded by the European Commission. The HelioClim-4 database is under creation in these MACC projects. It will contain 15 min values of the global, direct and diffuse components of the SSI with a daily update.

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Table 1. List of stations, ordered from north to south. Data from 2005 to 2009, except if stated otherwise.

Station	Country	Latitude	Longitude	Elevation (m)	Available summarization
Toravere	Estonia	58.250	26.467	70	15 min, 1 h, 1 day
Rucana	Latvia	56.150	21.167	18	1 day
Hamburg	Germany	53.633	10.000	16	1 day
Valentia	Ireland	51.933	−10.250	9	1 day
Uccle	Belgium	50.800	4.350	100	1 day
Camborne	UK (2004–2007)	50.217	−5.317	88	15 min, 1 h, 1 day
Vienna	Austria	48.250	16.367	203	1 day
Kishinev	Moldova (2005–2007)	47.000	28.817	205	1 day
Payerne	Switzerland	46.815	6.944	491	15 min, 1 h, 1 day
Carpentras	France	44.083	5.059	100	15 min, 1 h, 1 day
Nice	France	43.650	7.200	4	1 day
Thessaloniki	Greece (2005–2006)	40.633	22.967	60	1 day
Casablanca	Morocco (2005)	33.567	−7.667	62	1 day
Mersa Matruh	Egypt	31.333	27.217	25	1 day
El Arish	Egypt	31.083	33.750	31	1 day
Sede Boqer	Israel	30.905	34.782	500	15 min, 1 h, 1 day
Asyut	Egypt (2005–2007)	27.200	31.167	52	1 day
Aswan	Egypt	23.967	32.783	192	1 day
Tamanrasset	Algeria (2005–2007)	22.783	5.517	1378	15 min, 1 h, 1 day
Rochambeau	French Guiana	4.822	−52.365	4	1 day
Brasilia	Brazil (2006–2007)	−15.601	−47.713	1023	1 day
Bulawayo	Zimbabwe (2005)	−20.150	28.620	1343	1 day
Maputo	Mozambique	−25.967	32.600	70	1 day

Table 2. Comparison of correlation coefficients for 15 min irradiation and clearness index. Best values are in bold.

Station	I_{HC3v3}	$I_{\mathrm{HC3McClear}}$	$\mathrm{KT}_{\mathrm{HC3v3}}$	$\mathrm{KT}_{\mathrm{McClear}}$
Toravere	0.921	**0.924**	0.765	**0.773**
Camborne	0.950	**0.952**	0.829	**0.830**
Payerne	0.958	**0.959**	0.846	**0.853**
Carpentras	0.970	**0.972**	0.842	**0.845**
Sede Boqer	0.973	**0.975**	0.829	**0.846**
Tamanrasset	0.965	**0.970**	0.824	**0.830**

The HelioClim databases are available on the Internet through the SoDa website (http://www.soda-pro.com), and support research and business by providing data of known quality on surface solar irradiance. More than 100 000 requests were made in 2012 to HC1 by users and more than 2 million to HC3, demonstrating the large use of HelioClim databases. Lefevre et al. (2014) performed a review of the scientific literature citing HelioClim, and found many examples of usages in various domains: oceanography, climate, energy production, life cycle analysis, agriculture, ecology, human health, and air quality.

The HC1 and HC3 databases are derived from images of the Meteosat series of satellites using the Heliosat-2 method (Rigollier et al., 2004). The Heliosat-2 method needs a so-called clear-sky model to predict the SSI that should be observed under a clear sky. The European Solar Radiation Atlas (ESRA) clear-sky model (Rigollier et al., 2000) modified by Geiger et al. (2002) was selected, with the climatology of the Linke turbidity factor from Remund et al. (2003) as input. The Linke turbidity factor is a convenient approximation for modelling the atmospheric absorption and scattering of the solar radiation under clear skies. The climatology of Remund et al. (2003) comprises 12 maps, one per month, covering the world with cells of 5′ of arc angle in size. The use of this climatology is one of the drawbacks of the HC1 and HC3, and especially HC3, whose high temporal resolution (15 min) is in principle well suited for monitoring and reproducing rapid changes in SSI. Aerosols have different scattering and absorbing properties according to their type and the spatial and temporal heterogeneity of their number, size, chemical composition, and shape (Elias and Roujean, 2008; Xu et al., 2011). These properties as well as total column content in water vapour and ozone may vary rapidly within a day or from day to day, thus influencing the SSI under clear skies. Climatology cannot account for such changes, and HC3 estimates are often underestimated in the case of clear skies (Lefèvre et al., 2013). In addition, the Linke turbidity factor has a drawback inherent to its definition. It is a single value that summarises the effects of many variables. Simultaneous changes in these variables induce changes in irradiation under clear-sky conditions that may not be reflected in the Linke turbidity factor and therefore not in the irradiation estimated by the ESRA model.

The MACC and MACC-II projects are preparing the operational provision of global aerosol property analyses and forecasts together with physically consistent total column content in water vapour and ozone available every 3 h (Benedetti et al., 2011; Kaiser et al., 2012; Peuch et al., 2009). Up to now, a multi-annual reanalysis data set has been provided, and is used here (Inness et al., 2013). Such information has not been available so far from any operational numerical weather prediction (NWP) centre. A new clear-sky model called McClear has been developed to exploit this new input data source for estimating the direct and global SSI (Lefèvre et al., 2013). Validation of McClear outputs against beam and global irradiances measured at 1 min by BSRN stations in the world reveals satisfactory results. Good correlation is attained; bias, standard deviation and root mean square error (RMSE) are small (Lefèvre et al., 2013).

How can such advanced data sets on aerosol properties, water vapour and ozone be exploited to bring a significant improvement to the widely used HC3 without re-factoring the Heliosat-2 method and re-processing all Meteosat images since 2004? If this is possible, the dynamics of the aerosol properties, water vapour and ozone would be taken into account in the enhanced HC3, thus possibly yielding better estimates under clear-sky conditions. This technical note investigates the changes brought to HC3 in an a posteriori manner, i.e. by applying post-processing to the HC3 estimates, and assesses the benefit compared to the original HC3.

2 Data sets and method

The method is the following. A standard request to HC3v3 (version 3 of HC3) for a given site integrated over a given period, called summarization, e.g. 1 h or 1 day, yields several data, including the global SSI I_{HC3v3}, that under clear-sky condition I_{ESRA}, and I_0 the irradiance received on a horizontal surface at the top of atmosphere. The clear-sky index Kc is computed:

$$\mathrm{Kc} = I_{\mathrm{HC3v3}} \,/\, I_{\mathrm{ESRA}}. \tag{1}$$

The McClear model may be invoked through the SoDa website. It yields the clear-sky value I_{McClear} for the requested summarization and site, and the new version of the SSI $I_{\mathrm{HC3McClear}}$ is obtained:

$$I_{\mathrm{HC3McClear}} = \mathrm{Kc}\, I_{\mathrm{McClear}}. \tag{2}$$

A series of ground measurements of surface solar irradiation I_{ground} was assembled and serves as a reference in the comparison of I_{HC3v3} and $I_{\mathrm{HC3McClear}}$. Comparison was performed for the period 2005–2009. Measurements were collected from 23 stations located in the field of view of the Meteosat satellite.

Measurements of 15 min, hourly, and daily irradiation were collected at six stations of the BSRN (Baseline Surface Radiation Network). BSRN stations record global irradiation I_{ground} as well as its direct B and diffuse D components every minute. Roesch et al. (2011) recommend keeping only I_{ground} measurements that obey the following constraints:

$$\text{if } \theta_{\mathrm{S}} \le 75^\circ, 1.08 \ge (D+B)/I_{\mathrm{ground}} \ge 0.92 \tag{3}$$

$$\text{if } \theta_{\mathrm{S}} > 75^\circ, 1.15 \ge (D+B)/I_{\mathrm{ground}} \ge 0.85, \tag{4}$$

where θ_{S} is the solar zenith angle. Roesch et al. (2011) note a percentage of missing data of 4 % for global irradiance and 13 % for direct irradiance for all studied BSRN data. The original measurements passing Eq. (3) are summed up to yield 15 min, hourly and daily irradiation, provided a sum is made with at least 90 % valid measurements, e.g. 54 valid 1 min data to yield 1 h irradiation.

Measurements of daily irradiation were collected for another set of 17 stations of the meteorological networks archived in the WRDC (World Radiation Data Center) and available through the WRDC website. Table 1 lists the 23 stations that have been selected in order to represent various climates in Europe, Africa and tropical South America.

The clearness index KT, also called the global transmissivity of the atmosphere, or atmospheric transmittance, or atmospheric transmission, is defined as

$$\mathrm{KT} = I_{\mathrm{ground}} \,/\, I_0. \tag{5}$$

For clear skies, KT is close to 0.8, and is close to 0 for overcast skies. This index has the advantages of removing most of the effects due to sun position and indicating the type of sky. While irradiation for clear-sky conditions but a large solar zenith angle may be similar to that under cloudy conditions but with a low solar zenith angle, the clearness indices will be different. The clearness index is useful for analysing causes of discrepancies between the data sets. The clearness indices $\mathrm{KT}_{\mathrm{HC3v3}}$ and $\mathrm{KT}_{\mathrm{McClear}}$ are computed:

$$\mathrm{KT}_{\mathrm{HC3v3}} = I_{\mathrm{HC3v3}} \,/\, I_0 \tag{6}$$

$$\mathrm{KT}_{\mathrm{McClear}} = I_{\mathrm{HC3McClear}} \,/\, I_0. \tag{7}$$

The irradiation $I_{\mathrm{HC3McClear}}$, and hence the clearness index $\mathrm{KT}_{\mathrm{McClear}}$, are computed for each summarization: 15 min, 1 h, and 1 day:

$$(I_{\mathrm{HC3McClear}})_{\mathrm{hour}} = [(I_{\mathrm{HC3v3}})_{\mathrm{hour}} (I_{\mathrm{HC3McClear}})_{\mathrm{hour}}] \,/\, (I_{\mathrm{ESRA}})_{\mathrm{hour}} \tag{8}$$

$$(I_{\mathrm{HC3McClear}})_{\mathrm{day}} = [(I_{\mathrm{HC3v3}})_{\mathrm{day}} (I_{\mathrm{HC3McClear}})_{\mathrm{day}}] \,/\, (I_{\mathrm{ESRA}})_{\mathrm{day}}, \tag{9}$$

where the quantities $(I_{\mathrm{HC3McClear}})_{\mathrm{hour}}$, $(I_{\mathrm{HC3v3}})_{\mathrm{hour}}$, $(I_{\mathrm{HC3McClear}})_{\mathrm{hour}}$, $(I_{\mathrm{ESRA}})_{\mathrm{hour}}$, $(I_{\mathrm{HC3McClear}})_{\mathrm{day}}$, $(I_{\mathrm{HC3v3}})_{\mathrm{day}}$, $(I_{\mathrm{HC3McClear}})_{\mathrm{day}}$, and $(I_{\mathrm{ESRA}})_{\mathrm{day}}$ are directly retrieved from the SoDa website. Another approach could be to compute $I_{\mathrm{HC3McClear}}$ every 15 min, and then to perform the summarization for 1 h or 1 day, though this is less practical for the many users of the SoDa website.

Table 3. Comparison of differences for 15 min irradiation, in $\mathrm{J\,cm^{-2}}$. The mean value is obtained from the measurements. The first value is I_{HC3v3} and the second is $I_{\mathrm{HC3McClear}}$, with the best value in bold. Bias and RMSD of $I_{\mathrm{HC3McClear}}$ relative to the mean irradiation are given in brackets.

Station	Mean 15 min irradiation	Bias	Standard deviation	RMSD
Toravere	20.5	0.3 / −**0.1** (0 %)	7.9 / **7.8**	7.9 / **7.8** (38 %)
Camborne	23.2	**0.4** / 0.5 (2 %)	6.8 / 6.8	6.8 / 6.8 (29 %)
Payerne	25.5	−1.6 / −**0.3** (−1 %)	6.8 / 6.8	7.0 / **6.8** (27 %)
Carpentras	31.9	0.6 / 0.6 (2 %)	6.3 / **6.1**	6.4 / **6.2** (19 %)
Sede Boqer	47.6	−3.0 / −**1.8** (−4 %)	6.5 / **6.4**	7.1 / **6.6** (14 %)
Tamanrasset	47.6	**1.3** / 1.7 (4 %)	8.2 / **7.7**	8.3 / **7.8** (16 %)

Table 4. Comparison of differences for hourly irradiation, in $\mathrm{J\,cm^{-2}}$. The mean value is obtained from the measurements. The first value is I_{HC3v3} and the second is $I_{\mathrm{HC3McClear}}$, with the best value in bold. Bias and RMSD of $I_{\mathrm{HC3McClear}}$ relative to the mean irradiation are given in brackets.

Station	Mean hourly irradiation	Bias	Standard deviation	RMSD	Correlation coefficient
Toravere	76.8	1.1 / −**0.4** (−1 %)	25.9 / **25.2**	25.9 / **25.2** (33 %)	0.945 / **0.949**
Camborne	87.4	**1.6** / 2.0 (2 %)	21.5 / **21.2**	21.5 / **21.3** (24 %)	0.968 / **0.970**
Payerne	95.0	−5.9 / −**1.2** (−1 %)	20.9 / **20.8**	21.8 / **20.8** (22 %)	0.974 / **0.976**
Carpentras	120.4	2.3 / **2.2** (2 %)	20.6 / **19.7**	20.7 / **19.8** (16 %)	0.980 / **0.982**
Sede Boqer	184.3	−11.1 / −**6.8** (−4 %)	20.8 / **20.1**	23.5 / **21.2** (12 %)	0.984 / **0.985**
Tamanrasset	179.8	**4.9** / 6.5 (4 %)	27.1 / **24.4**	27.5 / **25.3** (14 %)	0.977 / **0.982**

For each summarization, the deviations $(I_{\mathrm{HC3v3}} - I_{\mathrm{ground}})$, $(I_{\mathrm{HC3McClear}} - I_{\mathrm{ground}})$, $(\mathrm{KT}_{\mathrm{HC3v3}} - \mathrm{KT}_{\mathrm{ground}})$ and $(\mathrm{KT}_{\mathrm{HC3McClear}} - \mathrm{KT}_{\mathrm{ground}})$ are computed and synthesised by the bias, the standard deviation, the root mean square difference (RMSD), and the correlation coefficient. Tables 2 to 5 report the results of the comparison for 15 min, hourly and daily irradiation respectively.

3 Results and discussion

The correlation coefficient for 15 min irradiation is reported in Table 2. For both I_{HC3v3} and $I_{\mathrm{HC3McClear}}$, the correlation coefficient is very large, greater than 0.95, except for Toravere (0.91), indicating that the 15 min irradiation is well reproduced by both estimates. The correlation is slightly greater for $I_{\mathrm{HC3McClear}}$ than for I_{HC3v3}, showing that the combination of I_{HC3v3} with McClear brings a better reproduction of the observed changes in irradiation. This observation is supported by the fact that the correlation coefficient for the clearness index $\mathrm{KT}_{\mathrm{McClear}}$ is greater than that for $\mathrm{KT}_{\mathrm{HC3v3}}$ (Table 2).

The bias for I_{HC3v3} ranges from −3.0 to 1.3 $\mathrm{J\,cm^{-2}}$ (Table 3). The bias for $I_{\mathrm{HC3McClear}}$ is similar to or smaller than that for I_{HC3v3} for all cases. An exception to the overall decrease in bias is Tamanrasset, where the bias is 1.3 $\mathrm{J\,cm^{-2}}$ (3 % of the mean irradiation) for I_{HC3v3} and 1.7 $\mathrm{J\,cm^{-2}}$ (4 %) for $I_{\mathrm{HC3McClear}}$. A closer examination of the data sets of irradiation and the clearness index for Tamanrasset reveals that I_{HC3v3} exhibits a negative bias for clear-sky conditions and a positive bias for cloudy situations. The balance between these negative and positive biases yields an overall bias of 1.3 $\mathrm{J\,cm^{-2}}$. The combination of I_{HC3v3} with McClear yields more accurate results for clear-sky conditions, as expected. The bias in these conditions is now strongly reduced and close to 0. On the contrary, there is almost no change in the results for cloudy situations, which exhibit a positive bias. Contrary to I_{HC3v3}, this positive bias is not counterbalanced in $I_{\mathrm{HC3McClear}}$ by an equivalent but negative bias for clear skies. The result is that the bias in $I_{\mathrm{HC3McClear}}$ is slightly greater than that of I_{HC3v3}.

The standard deviation is fairly similar for I_{HC3v3} and $I_{\mathrm{HC3McClear}}$ for all stations. It ranges from 6.3 to 8.2 $\mathrm{J\,cm^{-2}}$ for I_{HC3v3}. It is smaller for $I_{\mathrm{HC3McClear}}$, and ranges from 6.1 to 7.8 $\mathrm{J\,cm^{-2}}$. The smaller standard deviation may be linked to the better correlation coefficient observed for $I_{\mathrm{HC3McClear}}$. Similarly, the RMSD is slightly less for $I_{\mathrm{HC3McClear}}$ than for I_{HC3v3}. Tables 2 and 3 show that the combination of HC3 and McClear brings a benefit for 15 min irradiation for the six studied stations.

Table 4 reports results for hourly irradiation. The correlation coefficient for $I_{\mathrm{HC3McClear}}$ is large, greater than 0.97, except for Toravere (0.95), and is greater than that for I_{HC3v3}. The bias ranges from −11.1 to 4.9 $\mathrm{J\,cm^{-2}}$ for I_{HC3v3}, and from −6.8 to 6.5 $\mathrm{J\,cm^{-2}}$ for $I_{\mathrm{HC3McClear}}$. The bias for

Table 5. Comparison of differences for daily irradiation, in $\mathrm{J\,cm^{-2}}$. The mean value is obtained from the measurements. The first value is I_{HC3v3} and the second is $I_{\mathrm{HC3McClear}}$, with the best value in bold. Bias and RMSD of $I_{\mathrm{HC3McClear}}$ relative to the mean irradiation are given in brackets.

Station	Mean daily irradiation	Bias	Standard deviation	RMSD	Correlation coefficient
Toravere	1237	30 / **8** (1 %)	204 / **184**	206 / **184** (15 %)	0.969 / **0.974**
Rucana	1336	91 / **−11** (−1 %)	237 / **211**	254 / **211** (16 %)	0.966 / **0.971**
Hamburg	1112	−26 / **6** (1 %)	114 / **110**	117 / **111** (10 %)	0.989 / **0.991**
Valentia	1065	**42** / 49 (5 %)	200 / **188**	205 / **194** (18 %)	0.968 / **0.972**
Uccle	1113	−23 / **20** (2 %)	**108** / 110	**111** / 112 (10 %)	0.990 / **0.991**
Camborne	1150	**24** / 38 (3 %)	169 / **156**	171 / **160** (14 %)	0.978 / **0.982**
Vienna	1237	−36 / **0** (0 %)	119 / **124**	124 / 124 (10 %)	0.989 / 0.989
Kishinev	1348	37 / **21** (2 %)	171 / **154**	175 / **156** (12 %)	0.980 / **0.984**
Payerne	1275	−79 / **5** (0 %)	145 / **138**	165 / **138** (11 %)	0.985 / **0.987**
Carpentras	1552	28 / **27** (2 %)	162 / **126**	164 / **129** (8 %)	0.982 / **0.989**
Nice	1589	**48** / 60 (4 %)	152 / **130**	160 / **143** (9 %)	0.984 / **0.988**
Thessaloniki	1646	−74 / **3** (0 %)	128 / **102**	148 / **102** (6 %)	0.988 / **0.992**
Casablanca	1954	−45 / **−44** (−2 %)	176 / **172**	181 / **178** (9 %)	0.972 / **0.974**
Mersa Matruh	1853	**−36** / 52 (3 %)	185 / **165**	189 / **173** (9 %)	0.962 / **0.972**
El Arish	1754	**−16** / 53 (3 %)	205 / **177**	206 / **185** (11 %)	0.956 / **0.964**
Sede Boqer	2087	−128 / **−85** (−4 %)	151 / **134**	198 / **159** (8 %)	0.978 / **0.984**
Asyut	2092	94 / **84** (4 %)	**168** / 185	**193** / 204 (10 %)	**0.962** / 0.951
Aswan	2230	−26 / **15** (1 %)	**175** / 190	**177** / 191 (9 %)	**0.933** / 0.920
Tamanrasset	2319	**58** / 76 (3 %)	236 / **186**	229 / **170** (7 %)	0.903 / **0.951**
Rochambeau	1750	157 / **123** (7 %)	221 / **200**	271 / **234** (13 %)	0.927 / **0.934**
Brasilia	1964	205 / **162** (8 %)	257 / **228**	328 / **280** (14 %)	0.815 / **0.857**
Bulawayo	1948	**241** / 264 (14 %)	300 / **292**	**385** / 394 (20 %)	0.842 / **0.852**
Maputo	1801	180 / **65** (4 %)	215 / **201**	281 / **211** (12 %)	0.944 / **0.951**

$I_{\mathrm{HC3McClear}}$ is similar to or smaller than that for I_{HC3v3} for all cases.

The standard deviation ranges from 20.6 to 27.1 $\mathrm{J\,cm^{-2}}$ for I_{HC3v3}. In all cases, the standard deviation is smaller for $I_{\mathrm{HC3McClear}}$ than that for I_{HC3v3}, and ranges from 19.7 to 25.2 $\mathrm{J\,cm^{-2}}$. Like previously, the smaller standard deviation may be linked to the better correlation coefficient observed for $I_{\mathrm{HC3McClear}}$. The RMSD is less for $I_{\mathrm{HC3McClear}}$ than for I_{HC3v3}. It ranges from 19.8 to 25.3 $\mathrm{J\,cm^{-2}}$. Like for 15 min irradiation, Table 4 shows that the combination of HC3 and McClear brings a benefit for 1 h irradiation for the six studied stations.

Table 5 reports the results of the comparison for daily irradiation. The correlation coefficient for $I_{\mathrm{HC3McClear}}$ is large, greater than 0.93, except for Aswan (0.92), Brasilia (0.86) and Bulawayo (0.85). For all stations except Asyut and Aswan, the correlation is greater for $I_{\mathrm{HC3McClear}}$ than for I_{HC3v3}. The day-to-day changes in daily irradiation are well reproduced by I_{HC3v3}, and slightly better by $I_{\mathrm{HC3McClear}}$.

The bias ranges from −128 to 241 $\mathrm{J\,cm^{-2}}$ for I_{HC3v3}. The bias for $I_{\mathrm{HC3McClear}}$ is similar or smaller for 16 stations out of 23, and ranges from −85 to 264 $\mathrm{J\,cm^{-2}}$. Several stations exhibit spectacular decreases, such as Rucana (from 91 down to −11 $\mathrm{J\,cm^{-2}}$), Thessaloniki (from −74 down to 3 $\mathrm{J\,cm^{-2}}$), or Maputo (from 180 down to 65 $\mathrm{J\,cm^{-2}}$). Seven stations exhibit greater bias for $I_{\mathrm{HC3McClear}}$ than for I_{HC3v3}: Valentia, Camborne, Nice, Mersa Matruh, El Arish, Tamanrasset, and Bulawayo.

The standard deviation for $I_{\mathrm{HC3McClear}}$ ranges from 102 (Uccle) to 292 $\mathrm{J\,cm^{-2}}$ (Bulawayo). It is similar to or less than that for I_{HC3v3}, except for Asyut and Aswan. The RMSD for $I_{\mathrm{HC3McClear}}$ ranges from 102 to 394 $\mathrm{J\,cm^{-2}}$, that is, from 6 % to 20 % of the mean observed value. It is similar to or less than that for I_{HC3v3}, with the exception of Asyut, Aswan and Bulawayo. Actually, the difference in standard deviation or RMSD is small for these three sites, and is less than 15 $\mathrm{J\,cm^{-2}}$. This is less than the 66 % uncertainty required by the World Meteorological Organization for the measurement of the daily irradiation (WMO, 2008), which is 40 $\mathrm{J\,cm^{-2}}$ for $I_{\mathrm{ground}} < 800\,\mathrm{J\,cm^{-2}}$ and 5 % for $I_{\mathrm{ground}} > 800\,\mathrm{J\,cm^{-2}}$. Taking this into account, it is found that $I_{\mathrm{HC3McClear}}$ exhibits similar or better accuracy than I_{HC3v3} for daily irradiation.

One may observe that the relative RMSD for $I_{\mathrm{HC3McClear}}$ is less than 12 % in most cases. Exceptions are Toravere (15 %), Rucana (16 %), Camborne (14 %), Valentia (18 %), Rochambeau (13 %), Brasilia (14 %), and Bulawayo (20 %). These stations are seen with a large viewing angle by the Meteosat satellite. Schutgens and Roebeling (2009) or Marie-Joseph et al. (2013) argue that such angles induce a shift in the actual locations of clouds. The sensor aboard the Meteosat satellite does not see exactly what is happening in the atmospheric column right above a measuring station. This contributes to the deviation between HC3 and ground measurements. The effects of the parallax are enhanced in the case of fragmented cloud cover, especially when the pixel size is large, which happens for large viewing angles. Marie-Joseph et al. (2013) mention that cloud fragmentation may contribute to a larger bias for intermediate skies because of the limited spatial resolution of the Meteosat sensor that prevents one from detecting small broken clouds such as cumulus. This patchwork of small clouds may be interpreted by the sensor and furthermore by the Heliosat-2 method as a large thin cloud. This mistake contributes to the deviation. As a rule of thumb, the farther from the nadir of the Meteosat satellite located at latitude 0° and longitude 0°, and the greater the occurrence of fragmented cloud cover, the greater the bias, relative standard deviation and RMSD.

4 Conclusions

This technical note proposes a very simple method to improve HC3v3 records by combining them with data records of the irradiation under clear skies from the new McClear clear-sky model. Inputs to McClear are the advanced global aerosol property forecasts and physically consistent total column content in water vapour and ozone produced by the MACC projects. All irradiation data sets may be retrieved on the SoDa website (http://www.soda-pro.com), and therefore the method is easily applicable. The method can be applied at any scale; it is not necessary to correct HC3v3 at 15 min resolution and then to sum up to obtain hourly or daily irradiation. Hourly and daily irradiation can be corrected using the corresponding irradiation from McClear.

The method has been validated against ground measurements made at several summarizations: 15 min, 1 h, and 1 day. The correlation coefficient is large, greater than respectively 0.92, 0.94, and 0.97, for 15 min, 1 h and daily irradiation. The bias ranges from −4 to 4 % of the mean observed irradiation for most sites. The relative root mean square difference (RMSD) varies between 14 and 38 % for 15 min, 12 % and 33 % for 1 h irradiation, and 6 and 20 % for daily irradiation.

For all studied scales, 15 min, 1 h and 1 day, and almost all stations, the corrected irradiations $I_{\mathrm{HC3McClear}}$ are closer to the ground-based measurements than those of I_{HC3v3} obtained with a climatology of the Linke turbidity factor. There are few stations for which $I_{\mathrm{HC3McClear}}$ does not show better performances than I_{HC3v3}, and in these cases, the difference is not large, and is less than the 66 % uncertainty required for daily irradiation by the World Meteorological Organization (WMO, 2008). It is believed that the main cause of the benefit of this combination of HC3 and McClear is due to the fact that the inputs to McClear, aerosol properties and total column content in water vapour and ozone, are estimated every 3 h. The main advantage of combining HC3v3 and McClear is that the large irradiations are reproduced better. The method brings an improvement in most cases and no degradation in the others, and a systematic correction of HC3v3 with McClear is recommended.

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